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Aspects of seasonality and flood generating circulation patterns in a mountainous catchment in south-eastern Germany

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Abstract

Analyses of discharge series, precipitation fields and flood producing atmospheric circulation patterns reveal that two governing flood regimes exist in the Mulde catchment in south-eastern Germany: frequent floods during the winter and less frequent but sometimes extreme floods during the summer. Differences in the statistical parameters skewness and coefficient of variation of the discharge data can be found from west to east and are discussed in the context of landscape parameters that influence the discharge. Annual maximum discharge series were assigned to the triggering Großwetterlage in order to evaluate which circulation patterns are likely to produce large floods. It can be shown that the cyclone Vb-weather regime generates the most extreme flood events in the Mulde catchment, whereas westerly winds produce frequently small floods. Vb-weather regimes do not always trigger large flood events in the study area, but large floods are mostly generated by these weather patterns. Based on these findings, it is necessary to revise the traditional flood frequency analysis approach and develop new approaches which can handle different flood triggering processes within the dataset.

1 Introduction

Limited data on extreme and thus rare flood events complicate the accurate estimation of design discharges (e.g. Francés, 2001; Benito et al., 2004; Merz and Thieken, 2005). Numerous approaches have been developed for flood estimation, which include statistical approaches such as flood frequency analysis (FFA), the use of envelope curves as well as rainfall-runoff modelling with hydrological models. The focus in this study will be on the FFA.

The most common methods for FFA use annual maximum series (AMS) and peak over threshold series (POT) (Institute of Hydrology, 1999). AMS include one value for each hydrological year, whereas POT can also contain more than one value within a hydrological year, depending on the threshold. The AMS and POT series can also be extracted for summer or winter seasons, when, for instance, one flood process type (e.g. floods triggered by snow melting) is of special interest. Several distribution functions can be fitted to the data. These include for instance the Gumbel, Weibull, 2-parametric Log Normal, Generalized Extreme Value, General Logistics, 3-parametric Log Normal, Pearson type III, General Pareto distribution functions, which can be estimated with the Method of Moments, the maximum likelihood estimation or the L-Moments estimation (Hosking and Wallis, 1997; Institute of Hydrology, 1999). Although several distribution functions and possibilities, which data to integrate, exist, large uncertainties are still remaining when estimating extreme events. There is much debate about the minimal length of the data series and whether or not it is advantageous to use very long series, which may not reflect stationary conditions (e.g. Bárdossy and Pakosch, 2005; Khaliq et al., 2006). Moreover, it is questionable whether or not an AMS is stationary when the discharges reflect different flood producing processes. Usually, continuously measured time series with a length of at least 30 years of discharge and/or water level at gauge stations serve as the basis for the calculation and design of flood protection measures (DVWK, 1999). Independence, homogeneity and stationarity are required characteristics of the data to legitimate flood frequency analysis (Stedinger, 2000; Kundzewicz and Robson, 2004). However, often these criteria are not satisfied due to climatic change and/or anthropogenic influence (Webb and Betancourt, 1992; Klems, 1993; Jain and Lall, 2001; Sivapalan et al., 2005; Svenson et al., 2005; Khaliq et al., 2006). Independence is almost always given, when analyzing annual maximum series, whereas partial series have to be carefully examined in order to avoid miscounting one flood event as two. Stationary conditions seldom exist due to changes in climate, land-use or in the vulnerability of the study area, although these are often assumed (Merz, 2006). Moreover, the dynamics of atmospheric processes and flood generation have to be taken into account in the study of stationarity and independence and further in the FFA (Merz and Blöschl, 2003; Sivapalan et al., 2005).

The relationship between climate and flood generation has been of growing interest

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and study (Webb and Betancourt, 1992; Kästner, 1997; Jain and Lall, 2000; Bárdossy and Filiz, 2005; Steinbrich et al., 2005; St. George, 2007). Steinbrich et al. (2005) analyze the correlation between circulation patterns and heavy rain for the south-western part of Germany (Baden-Wuerttemberg). Kästner (1997) found that only five different weather patterns are susceptible to produce flood events in Bavaria. Three catchments in southern Germany (Bavaria), which have different discharge characteristics and are differently influenced by snow melting, were studied. Kästner (1997) found the Vb-weather regime to be most susceptible for the generation of large floods. This weather system is a low pressure system that moves very slowly from the Gulf of Genoa northwards. It can accumulate large amounts of moist and warm air over the Mediterranean Sea, which is transformed into large precipitation amounts that fall along the northern slopes of the Alps and mountain ranges in Central and Eastern Europe. It is therefore interesting to analyze the relationship of circulation patterns and flood generation in the study area.

More information about flood generating processes can be gained when extending the study from one gauge station to the hydrological behaviour of sub-catchments and neighbouring regions (Harlin and Kung, 1992; Merz et al., 2006; Ouarda et al., 2006). Harlin and Kung (1992) extract for each sub-catchment the most extreme measured events and simulate the simultaneous occurrence of the floods which has not been observed yet. Of special interest for the flood hazard estimation of ungauged areas is also the regional FFA which incorporates flood process information from neighbouring catchments (e.g. Stedinger, 1983; Hosking and Wallis, 1997; Institute of Hydrology, 1999). Regionally valid distribution functions are fitted to data of preferably independent gauges within a region, which exhibit, in general, better fits (Merz, 2006).

In this paper the flood discharge characteristics of the Mulde catchment in south-eastern Germany are discussed from different points of view. Data of 15 discharge gauges are analyzed according to stationarity, their spatial distribution of the statistical moments and the relationship between landscape characteristics and flood peaks. Additionally, the relationship between the dominating weather pattern in Europe and the flood generation in this catchment is discussed.

2 Study area and data

2.1 Study area

The Mulde catchment is a sub-catchment of the Elbe River basin in south-eastern Germany. The southern boundary is marked by the mountain ranges of the Erzgebirge, which coincides with the Czech – German border. The catchment has a total area of 6171 km^2 (at the gauge Bad Düben) and has three large sub-catchments (Zwickauer Mulde, Zschopau, Freiberger Mulde), which drain the upper, mountainous part of the catchment (Fig. 1). Within only 20 kilometers, the tributaries Zschopau and Freiberger Mulde disembogue near the gauge Erlln (gauge 13, Fig. 1) into the Zwickauer Mulde and form the Vereinigte Mulde ("Joined Mulde"), which disembogues near the city of Dessau into the Elbe River.

The elevation ranges from 52 m to 1213 m a.s.l. with approx. 2/3 of the area being lowlands and 1/3 mountains (500–1213 m a.s.l.) (Fig. 1). The mountain ranges in the south cause fast runoff responses to rainfall events in the tributaries, whereas in the major part of the catchment slower runoff responses dominate. The annual precipitation ranges from 500 mm in the lowlands to 1100 mm in the mountain ranges.

The landscape characteristics of the catchment such as geology, soil, hydro-geology, land-use and relief parameters were evaluated to gain information about their influence on the discharge behaviour. Therefore, the catchment was split into zones with similar soil, geology and groundwater reservoirs. These zones correspond to the elevation: In the upper part of the Erzgebirge (sub-catchments Zwickau-Poelbitz, Lichtenwalde, Berthelsdorf; discharge locations 3, 9, 11 in Fig. 1), Cambisols can be found with underlying volcanic rocks which have no groundwater reservoirs. In the western part along the Zwickauer Mulde some smaller groundwater reservoirs exist which are fed from sand-mudstone interbedded stratification. Noteworthy groundwater areas can

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only be found in the northern lowlands. Along the Vereinigte Mulde also alluvial clays are present.

The land-use is dominated by forests and agriculture (Fig. 2). The mountains are mainly covered by forests, and intensive agriculture is found in the lowlands. The proportion of agriculturally-used areas increases from west to east and south to north, whereas the percentage of forest decreases. Urban areas only play a role in the sub-catchment Zwickauer Mulde with two larger cities (Zwickau, Chemnitz). Meadows and pastures are homogenously distributed across the area with a slightly larger area in the upper middle Erzgebirge (Fig. 2).

The region has a vital history of large flood events. First written documents about floods, the corresponding water levels and damage can be found from the 9th century onward and more detailed documents starting from the 14th century (Pohl, 2004). It is noteworthy that both large winter floods with ice blockage as well as summer floods from torrential storms or long lasting frontal rains caused high damages.

During the last 100 years, three extreme flood events occurred in the study area, namely in July 1954, July 1958 and August 2002. These events will be analyzed in more detail in this paper. All of them were caused by large torrential storms. The floods in 1954 and 2002 were triggered by Vb-weather systems. Both flood events in the fifties caused high damage in different parts of the catchment, whereas in 2002 the entire catchment was affected. On the 12 August 2002, a daily precipitation height of 312 mm was measured in Zinnwald-Georgenfeld (near the study area) – the largest value in Germany since the beginning of regular measurements (DWD, 2003; Ulbrich, 2003). This flood caused a damage of 11 600 Million €in Germany alone (DKKV, 2004; Thieken et al., 2006).

As a consequence of the flood history, flood defence measures play an important role and have been extended until the present day (DKKV, 2004). Numerous flood retention basins and dams were constructed, which are mainly located in the upper part of the catchment, and influence significantly the discharge downstream. Altogether, 77 dams protect the catchment against flooding, provide drinking water and produce electricity.

22 dams belong to the Class 1 of the Saxonian Dam Classification which comprises constructions with dam heights of more than 15 m or reservoir volumes of at least 1 Mio. m^3 (LfUG, 2002).

2.2 Data

2.2.1 Discharge data

Over 60 discharge and water level gauges exist in the Mulde catchment. The earliest measurements at regular intervals began in 1910 at two gauges. In order to evaluate the influence of dam constructions before including data from the downstream discharge gauge into the dataset, daily differences of inflow versus outflow of five large dams for the period 1991–2002 were compared. More information from the dam authorities was not available. Inflow and outflow flood peaks were compared and the downstream stations were excluded from the dataset if the flood peak differences were greater than 10%, and if there were at least five affected flood events during this 10 year period. Additionally, daily time series of discharge gauges that are in the immediate vicinity of a dam were compared to daily discharge data from neighbouring gauges at other tributaries. Time series of discharge gauges that did not reflect the hydrograph at the compared gauge station were excluded from the dataset. In order to evaluate the influence of a dam before including data from the downstream discharge gauge into the dataset, daily differences of inflow versus outflow of five large dams for the period 1991–2002 were compared. More information from the dam authorities was not available. Inflow and outflow flood peaks were compared and the downstream stations were excluded from the dataset if the flood peak differences were greater than 10%, and if there were at least five affected flood events during this 10 year period. Additionally, daily time series of discharge gauges that are in the immediate vicinity of a dam were compared to daily discharge data from neighbouring gauges at other tributaries. Time series of discharge gauges that did not reflect the hydrograph at the compared gauge station were excluded from the dataset. Annual maximum discharge series (AMS) (hydrological year from November to October) were extracted from daily maximum discharges.

A subset of discharge gauges was selected for this analysis which met the following criteria: 1) the time series must have a length of at least 40 years, 2) the sub-catchment area is larger than 100 km^2, 3) the flood AMS exhibits no trend, 4) the discharge gauges are distributed across the catchment and have a distance of at least 3 km among each other.

15 discharge gauges meet these criteria; they are listed in Fig. 1 and Table 1. For better readability, the gauge stations are listed in all tables in the same order beginning with those located in the south-west (Zwickauer Mulde), then progressing north and east (Zschopau, Freiberg Mulde) and ending with gauges located in the Vereinigte Mulde (cf. Fig. 1).

2.2.2 Precipitation data

Precipitation data were available from the German Weather Service (DWD) at 49 stations in and around the Mulde catchment (see Fig. 3). The data cover the time period between 1952 and 2002 on a daily basis. Daily areal precipitation was calculated based on cubic interpolation for each of the 15 sub-catchments (corresponding to the discharge stations) for the comparison of precipitation and discharge.

2.2.3 Atmospheric circulation patterns

Information about the predominant European circulation pattern for each day was available from the "Catalogue of Großwetterlagen[1] in Europe 1881–2004" (Gerstengarbe and Werner, 2005). The catalogue distinguishes three large circulation patterns, which are divided into 30 different Großwetterlagen (one is classified to be a "transition class") (Table 2).

[1]Großwetterlage: weather pattern with a certain atmospheric pressure distribution (500 hPa), geographical extent and direction.

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The circulation patterns comprise the zonal circulation form, the mixed circulation form as well as the meridional circulation form. For every day a Großwetterlage is assigned to be the dominant one for Europe. Through the specific distribution of lows and highs over Europe, it may therefore be possible that the dominant Großwetterlage of a particular day is not necessarily representative for the Mulde catchment. This is for instance the case, if the Mulde catchment is still under the influence of a weakened low, which is however already situated above Eastern Europe, whereas the dominating European Großwetterlage is above Western Europe. However, other than this catalogue, more detailed meteorological data for the study area were not available.

3 Methodology

3.1 Flood frequency analysis

The distribution-free and non-parametric Mann-Kendall test for Trend (one-sided test; significance level: α=0.05) was used for the detection of trends in the data. Since small trends in the data may not be detectable, for instance by the Mann-Kendall test (Bárdossy and Pakosch, 2005), a regional test of stationarity was conducted with all 15 data sets (Lindström and Bergström, 2004). To this end, several data series from the same region, that cover the same period of measurements, are tested jointly (also with the Mann-Kendall test). For comparison, the discharge data were divided by the MHQ (mean flood discharge) of the respective series. AMS of 13 gauge stations with data from 1936 to 2002 and of two gauges with data from 1961 to 2002 were included.

Independence of the data was ensured by using AMS data, which were also checked for possible dependent values around the turn of a hydrological year. For this, a threshold time of 7 days between two AMS floods was included, which guarantees the independence of two close-by flood events.

Flood frequency analyses were performed with seven different distribution functions (Gumbel, Weibull, 2-parametric LogNormal, Generalized Extreme Value, General Logistics, 3-parametric LogNormal, Pearson type III) with both the Method of Moments and with the L-Moments (Hosking and Wallis, 1997; Institute of Hydrology, 1999). The GEV (Generalized Extreme Value) distribution function and the General Logistics distribution function (both with L-Moments) revealed the best fits based on the Kolmogorov-Smirnov-Test and visual examination relative to the empirical probabilities. Emerging consensus can be found in many studies worldwide that the GEV distribution reveals the best fits (Pearson, 1991; Onoz and Bayazit, 1995; Vogel and Wilson, 1996; Douglas and Vogel, 2006). The Institute of Hydrology (1999) also describes the "theoretical and historical importance" of the GEV. Hence, subsequent analyses were performed using the GEV.

3.2 Spatial distribution of flood characteristics

The spatial distributions of the statistical moments of the AMS, such as skewness and coefficient of variation, were analyzed to detect possible differences among sub-catchments. The spatial extent and distribution of the three most extreme flood events (July 1954, July 1958, August 2002) were analyzed in more detail. For every event and gauge station, return periods (GEV, L-Moments) were calculated. These estimates were then assigned to each river segment upstream of the 15 gauge stations in order to analyze the flood characteristics in a spatially explicit manner.

Moreover, the AMS of 11 gauge stations with data from 1929 to 2002 (74 years) were studied with respect to the spatial distribution and magnitude of flood events. To this end, the number of different flood events per year in the catchment was analyzed. If all 11 gauges have their highest discharge of a certain year on the same day (+/–1 day), the number of flood events for that year will be one. The other extreme is that all gauges have their highest peak at another time of the year. In that case, the number of flood events for that year is 11.

3.3 Relationship between precipitation maxima and discharge maxima

The relationship between precipitation maxima and discharge maxima was studied in more detail. Areal precipitation was calculated for the three large sub-catchments (Zwickauer Mulde: gauge Wechselburg; Zschopau: gauge Lichtenwalde; Freiberger Mulde: gauge Nossen) and the Vereinigte Mulde at the gauge Golzern. Precipitation sums of 24 h, 48 h and 72 h of the flood events were compared to discharge maxima. The four discharge stations are distributed over the entire catchment and represent the large sub-catchments. Rainfall AMS were extracted from the precipitation data and then compared on a seasonal basis to the discharge AMS to determine, how many large precipitation events are reflected in the discharge AMS.

3.4 Circulation pattern and flood generation

Daily data of Großwetterlagen between 1911 and 2002 were analyzed in order to obtain an overview about the seasonal distribution and frequency of the circulation patterns in Europe. Additionally, the Großwetterlagen, which triggering the AMS discharges, were manually assigned to the AMS flood data of the gauge Golzern. The gauge at Golzern on the Vereinigte Mulde was selected to be representative for the entire catchment. It comprises 88% of the entire catchment and has a long time series (1911–2002).

From the AMS data, empirical probabilities were assigned to the flood events and then combined with the Großwetterlagen data. With this information, it is possible to estimate the potential of a Großwetterlage to generate a flood of a certain return period.

4 Results

4.1 Testing for trends in the flood AMS

Stationarity was tested for all 15 discharge AMS with the one-sided Mann-Kendall test for increasing trend (significance level α=0.05). No trends were detected. The trend test for regional stationarity was performed with the normalized AMS of the 15 gauge stations. As Fig. 4 shows, the data exhibit a very small positive trend in the regional trend analysis. When the flood event from August 2002 was excluded from the data, the slightly positive trend became slightly negative. The Mann-Kendall test showed no trend (significance level α=0.05). Therefore the data can be used for flood frequency analysis.

4.2 Seasonal occurrence and magnitude of floods

Two dominant flood process types in the Mulde catchment can be extracted from the data. During March and April, a first peak in the discharge AMS occurs during snow melt and "rain on snow" flood events. The second peak occurs in July and August, when large torrential storms traverse the area (Table 3). At all 15 discharge stations winter floods (November–April) occur more often than summer floods. In the upper western part of the Erzgebirge (corresponding to the gauges at Aue, Niederschlema, Zwickau), the percentage of summer and winter floods is almost equal (e.g. Aue: 46% summer floods; 54% winter floods), whereas in the eastern part of the catchment winter floods have larger percentage (59%–69%).

Figure 5 shows the monthly distribution of the discharge AMS at the four gauges at Aue, Lichtenwalde, Nossen and Golzern. In the diagrams, discharges are plotted as circle histograms (12 axes for 12 months; clockwise). The distance of each point from the centre represents the magnitude of the flood event. The winter floods are usually small events with a low return period. They constitute only 20% of the largest floods (8–16%). Summer flood events, on the other hand, are less frequent, but cover a larger proportion of extreme events (26–39%). In Fig. 6 the data of Table 3 are summed up for all 15 gauges. Additionally, the monthly distribution of the 20% largest flood events is shown. From these analyses we can conclude that summer flood events play an important role for the flood hazard estimation of extreme events.

4.3 Spatial distribution of flood characteristics

The discharge data were analyzed with respect to the spatial distribution of statistical moments (skewness, coefficient of variation). Surprisingly, more similar statistical moments were found along the tributary rivers rather than according to the elevation the of the gauge locations. The assumption could be made that the gauges in the mountains of the Erzgebirge can be grouped together to exhibit similar statistical moments as well as the gauges in the lowlands. However, an increase of the statistical moments occurs from west to east that corresponds to the division of the sub-catchments. Figure 7 shows the spatial distribution of the skewness (A) and the coefficient of variation (B) for the 15 gauges. It can be clearly seen that the sub-catchment of the Zwickauer Mulde is more homogeneous in its statistical moments. Moreover, the range of the skewness and the maximum skewness value are lower in the Zwickauer Mulde sub-catchment (2.6–3.0) than in the other sub-catchments (3.0–6.7).

The AMS of 11 gauge stations with data from 1929 to 2002 (74 years) were studied with respect to the spatial distribution and magnitude of flood events. To this end, the number of different flood events per year in the catchment was analyzed. In 13 years of the 74-years period, one flood event occurred affecting all 11 sub-basins, whereas in 18 years no dominant flood event (i.e. four to seven flood events per year) could be identified. Figure 8 illustrates that in most years (27), three different flood events caused AMS discharges.

In Fig. 9 six different flood events at the 11 analyzed gauges and their respective return periods are shown. The return periods were estimated with the GEV (L-Moments). Discharges that correspond up to a 10-year peak discharge are mostly homogenously distributed across the catchment and have similar return periods at the different gauges. This is shown in the diagrams, which represent the floods in January 1938, October 1960 and August 1984. Discharges larger than a 10-year peak exhibit increasing spatial distinctions. This is illustrated in Fig. 9 by the diagrams of the floods in 1954, 1958 and 2002. Depending on the location of the precipitation field, one or the other sub-catchment is more affected during a large flood event.

Figure 10 shows the spatial distribution of the return periods that were calculated for the observed discharges of the three most extreme flood events (1954, 1958, 2002) in the Mulde catchment (upper part) and the corresponding areal precipitation events (lower part). The return period calculated for a certain gauge was assigned to the river segment upstream of the gauge. A marked spatial distribution can be seen. For the flood event in 1954, high return periods were calculated for the western part of the catchment. This is explained by the rainfall event that had its centre in the western part. The floods in 1958 and 2002 were caused by precipitation events with their centres east of, or in the eastern part of the study area. Figure 10 illustrates the direct relationship between the location of the precipitation field and the flood return period for the three events.

4.4 Relationship between precipitation AMS and discharge AMS

The preceding Sect. 4.3 showed that landscape characteristics, such as elevation and land use, have a minor influence on the statistical flood characteristics. The dominant influence seems to be exerted by precipitation and weather characteristics. AMS of precipitation and discharge were therefore compared to determine how well precipitation and discharge AMS coincide. Different precipitation AMS were extracted from sums of one, two and three days. A time lag of two days between the precipitation event and the discharge peak was allowed. Table 4 shows the percentages of agreement for summer and winter separately for four discharge stations.

During the winter, the precipitation events are not so clearly and directly reflected in the discharge data (agreement 7–26 %). One reason for this can be found in the topography of the catchment. During the winter time, large amounts of the precipitation can fall as snow in the Erzgebirge and the water is stored in the snowpack. The discharge generation is delayed until melting starts. Therefore, the triggering Großwetterlage, which may have brought a major snow cover, cannot be directly related to the corresponding discharge peak. On the contrary, a direct connection between a large summer rain event and a large discharge can be found in the summer throughout the catchment (agreement 59–89%). Based on these findings the question was posed if large summer flood events can also be related to a specific circulation pattern. This question will be answered in the following section.

4.5 Circulation pattern, Großwetterlage and flood generation

First of all, daily information about the dominating European Großwetterlage between 1911 and 2002 at the gauge Golzern were analyzed. For the entire period, westerly winds cover about 25% of the total circulation patterns; high pressure weather regimes cover about 27%. The proportion of the Vb-weather regimes is relatively low with 6.5%.

The analysis of the discharge AMS shows that approx. 60% occur during the winter time and 40% during the summer time. Only 19 out of the 30 Großwetterlagen (cf. Table 2) play a role in creating AMS discharges in the Mulde catchment. Thus, 11 out of 30 Großwetterlagen have not created an AMS discharge within the 92 years. In the winter (November–April), the cyclonal western and north-western Großwetterlagen (WA–WW; NWZ) play the dominant role in flood generation, because they account for 84% of the AMS winter discharges and 100% for the floods from November until February (see Fig. 11). The summer AMS discharges are generated by several different Großwetterlagen, though mainly by westerly cyclones (WA-WW), north-east cyclones (NEZ) and the troughs over central Europe (TM, TRM). Figure 12 illustrates the distribution of the Großwetterlagen, separately for summer and winter.

To answer the question, which Großwetterlage is likely to generate large floods in the Mulde catchment, the flood potential of different circulation patterns was calculated as probability for a flood quantile HQ_T, given a certain Großwetterlage:

$$P\left(HQ_T|\mathrm{GWL}_X\right) = \frac{n_{HQ_T}}{n_{\mathrm{GWL}_X}} \tag{1}$$

where n_{HQ_T} is the number of flood events larger than HQ_T (e.g. the 10-year flood) that have been triggered by a certain Großwetterlage GWL_X, whereas n_{GWL_X} is the number of days with the corresponding Großwetterlage. It is important to note that already for small return periods (5 years) the Vb-Großwetterlagen have the highest flood potential (Fig. 13). Although these Großwetterlagen occur seldom, they are associated with high discharge peaks. Their flood potential is even more pronounced for floods of larger return periods. Weather patterns, such as the westerly and north-western cyclones, which are responsible for most of the winter AMS discharges, play only an important role for return periods of max. 10 years.

There exist also Vb-weather regimes that generated floods with low return periods at the gauge Golzern. However, they often caused high damage in other catchments in Europe and had their precipitation centre outside the Mulde catchment. This is for example the case for the flood in April 1930 in Bavaria, the August 1984 flood in Switzerland, and the flood in July 1997 in the Odra catchment, when the Czech Republic and Poland were heavily affected (Grünewald et al., 1998; Wasserwirtschaftsamt Bayreuth, 2006).

Analyses of the other gauge stations as well as historical records of large floods in the Mulde catchment show similar results with the highest floods being generated by Vb-weather regimes. From this analysis we can conclude that although Vb-weather pattern do not occur often in the European weather regime they carry a large flood risk in the Mulde catchment.

5 Conclusions

Analyses of discharge series, precipitation fields and flood producing atmospheric circulation patterns revealed two governing flood regimes in the Mulde catchment in south-eastern Germany: (1) frequent floods during the winter with generally low return periods and (2) less frequent floods during the summer, which can reach remarkable flood peaks. Differences in the statistical parameters skewness and coefficient of variation of the discharge data are found in the catchment from west to east, which are however not reflected in the landscape characteristics such as soil, elevation or land-use. It is suspected that the location and the duration of the precipitation field are the most influencing factors for the discharge.

Annual maximum discharge series were assigned to the triggering Großwetterlage to evaluate which circulation patterns are likely to produce large floods. It can be shown that the cyclone Vb-weather regime generates the most extreme flood events in the Mulde catchment whereas westerly winds produce frequent and hence small floods. Vb-weather regimes do not always trigger large flood events in the study area, but large floods are mostly generated by these weather patterns.

Based on our findings we suggest that the usual approach to estimate large floods through the FFA should be supplemented by the analysis of landscape catchment characteristics and especially by the analysis of the flood producing weather regimes. In view of the climate change it is important to gain information about weather regimes that trigger large flood hazards in the region of interest and how to integrate this information into the flood frequency analysis. Based on these findings, it is then necessary to revise the traditional FFA approach and develop new approaches which can integrate different flood triggering processes within the dataset.

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Table 1. Analyzed discharge gauges in the study area (* stations with one year of missing values).

Number	Gauge	Basin area [km^2]	Elevation [m a.s.l.]	Period of Measurements	Mean flood discharge [m^3/s]	Highest value of observation period [m^3/s]
1	Aue 1	362	349	1928-2002	66	315
2	Niederschlema*	759	314	1928–2002	111	585
3	Zwickau-Poelbitz*	1030	255	1928–2002	128	683
4	Wechselburg 1	2107	160	1910–2002	213	1000
5	Streckewalde	206	410	1921–2002	30	145
6	Hopfgarten*	529	357	1911–2002	81	420
7	Pockau 1	385	397	1921–2002	69	449
8	Borstendorf	644	356	1929–2002	91	540
9	Lichtenwalde	1575	253	1910–2002	218	1250
10	Kriebstein UP	1757	183	1933–2002	231	1350
11	Berthelsdorf	244	377	1936–2002	35	360
12	Nossen 1	585	204	1926–2002	69	690
13	Erlln	2983	133	1961–2002	329	1550
14	Golzern 1*	5442	118	1911–2002	517	2600
15	Bad Dueben 1	6171	82	1961–2002	474	1760

Table 2. Classification of the circulation patterns and Großwetterlagen.

Form of Circulation	No.	Großwetterlage Name	Abbr.
Zonal Circulation	1	West wind, anti-cyclone	WA
	2	West wind, cyclone	WZ
	3	Southern west wind	WS
	4	Angular west wind	WW
Mixed circulation	5	South-west wind, anti-cyclone	SWA
	6	South-west wind, cyclone	SWZ
	7	North-west wind, anti-cyclone	NWA
	8	North-west wind, cyclone	NWZ
	9	High pressure system, middle Europe	HM
	10	High pressure circuit over middle Europe	BM
	11	Low pressure system, middle Europe	TM
Meridional circulation	12	North wind, anti-cyclone	NA
	13	North wind, cyclone	NZ
	14	High pressure Iceland, anti-cyclone	HNA
	15	High pressure Iceland, cyclone	HNZ
	16	High pressure, British Isles	HB
	17	Trough Middle Europe	TRM
	18	North-east wind, anti-cyclone	NEA
	19	North-east wind, cyclone	NEZ
	20	High pressure Fennoscandia, anti-cyclone	HFA
	21	High pressure Fennoscandia, cyclone	HFZ
	22	High pressure Norwegian Sea-Fennoscandia, anti-cyclone	HNFA
	23	High pressure Norwegian Sea-Fennoscandia, cyclone	HNFZ
	24	South-east wind, anti-cyclone	SEA
	25	South-east wind, cyclone	SEZ
	26	South wind, anti-cyclone	SA
	27	South wind, cyclone	SZ
	28	Low Pressure, British Isles	TB
	29	Trough, Western Europe	TRW
	30	Transition, no classification	U

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Table 3. Monthly absolute frequency of discharge AMS.

Gauge	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
Aue	6	3	7	18	6	4	11	6	5	3	2	4	75
Niederschlema	4	4	9	17	6	6	11	5	3	3	1	5	74
Zwickau	3	4	8	15	6	7	12	5	3	3	2	6	74
Wechselburg	11	7	12	8	5	7	16	8	1	2	5	11	93
Streckewalde	9	7	13	14	4	6	14	7	0	3	1	4	82
Hopfgarten	12	9	13	10	6	7	11	6	1	5	1	10	91
Pockau	9	9	14	8	8	5	10	6	2	3	2	6	82
Borstendorf	6	7	15	10	7	4	8	5	1	3	2	6	74
Lichtenwalde	12	13	18	9	6	5	8	8	1	2	1	10	93
Kriebstein	6	8	13	10	5	5	7	5	1	2	1	7	70
Berthelsdorf	5	9	16	5	6	2	7	5	1	1	1	9	67
Nossen	8	12	18	4	5	3	7	5	2	2	2	9	77
Erlln	4	5	11	4	3	1	3	5	1	1	0	4	42
Golzern	13	11	15	8	5	6	10	8	2	3	3	7	91
Bad Düben	4	4	11	5	3	1	4	4	1	1	0	4	42
Sum	112	112	193	145	81	69	139	88	25	37	24	102	

Table 4. Percentages of agreement between precipitation AMS (precipitation sums of 24 h, 48 h and 72 h) and discharge AMS.

Gauge	24 h Summer	Winter	48 h Summer	Winter	72 h Summer	Winter
Wechselburg	65%	7%	61%	7%	70%	10%
Lichtenwalde	88%	20%	88%	7%	71%	14%
Nossen	78 %	15 %	89 %	26 %	83 %	26 %
Golzern	59%	20%	68%	17%	68%	20%

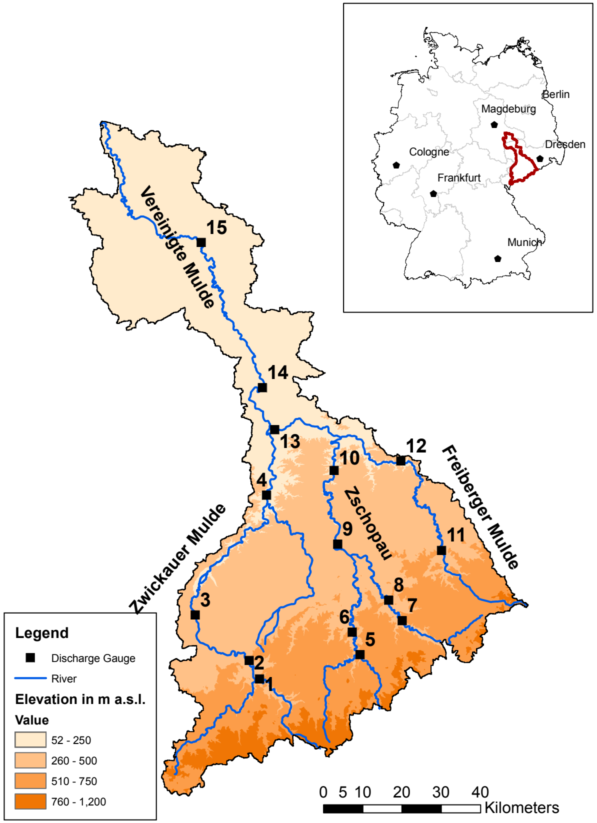

Fig. 1. Study area Mulde catchment: left: discharge gauge locations (numbered according to Table 1) and the digital elevation model; right: geographical location in Germany.

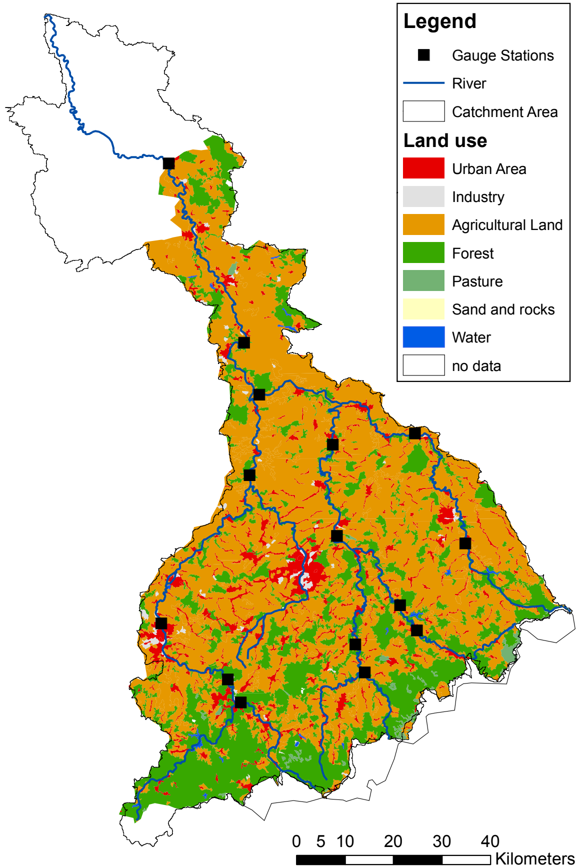

Fig. 2. Spatial distribution of land use in the Mulde catchment.

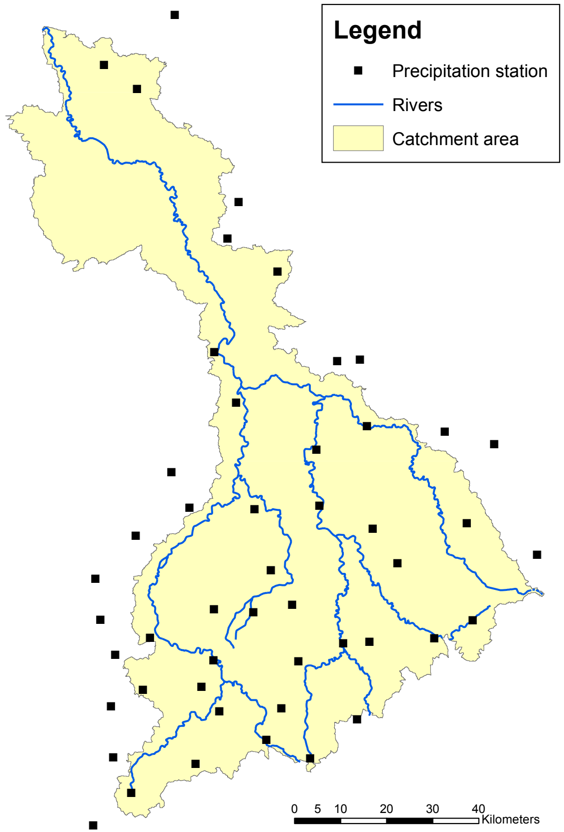

Fig. 3. Locations of the 49 precipitation stations in and around the study area.

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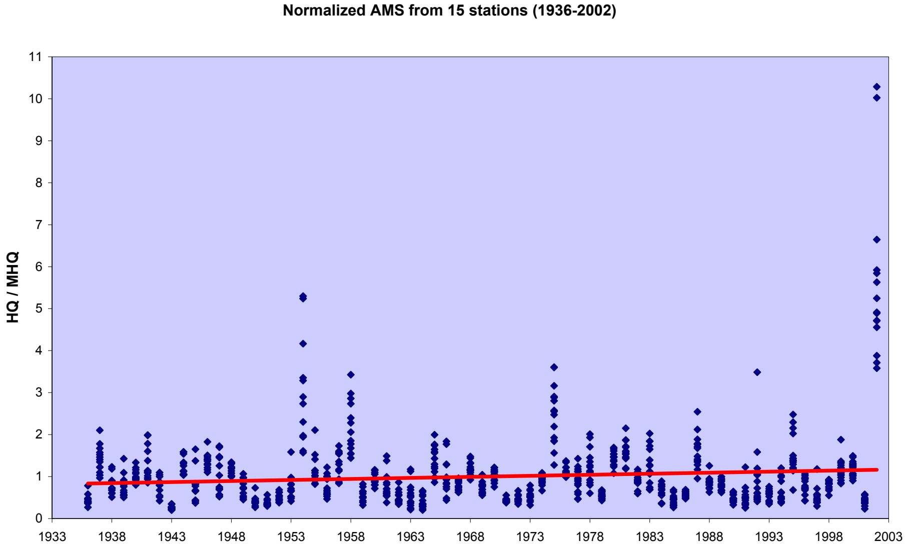

Fig. 4. Regional trend test based on discharge data of 15 stations.

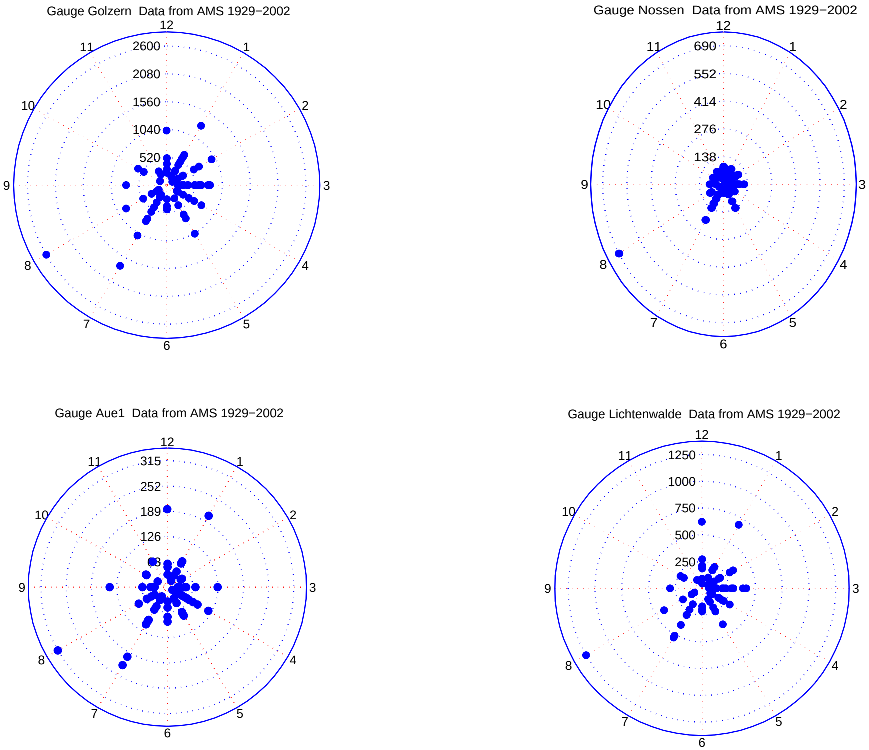

Fig. 5. Monthly distribution of discharge AMS at Golzern, Nossen, Aue, Lichtenwalde; (circle histograms: 1: January … 12: December; Ordinate: discharge in [m^3/s]).

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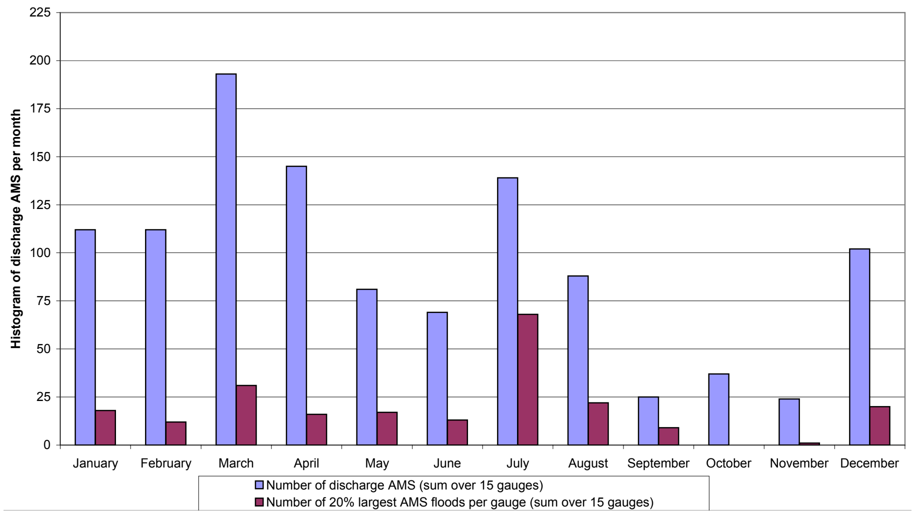

Fig. 6. Monthly distribution of the number of discharge AMS, summed up over the 15 gauges for all AMS floods and for the 20% largest events.

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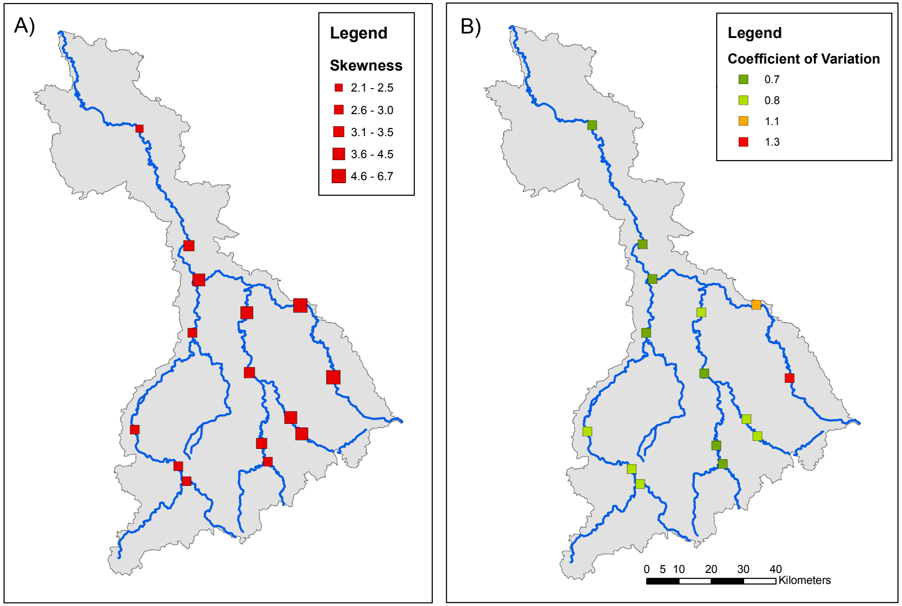

Fig. 7. Skewness **(A)** and coefficient of variation **(B)** of the discharge AMS for the 15 gauges.

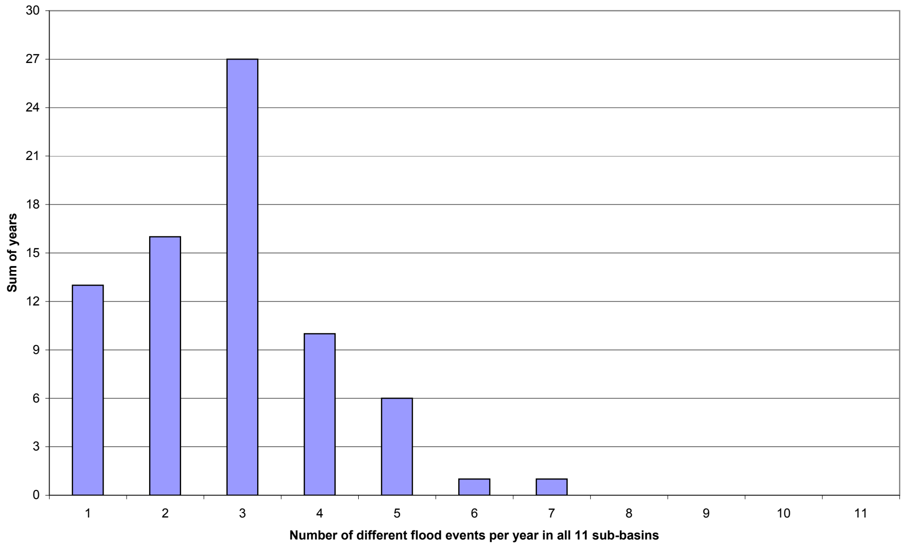

Fig. 8. Histogram showing the number of different floods, which created AMS discharges in 11 sub-catchments.

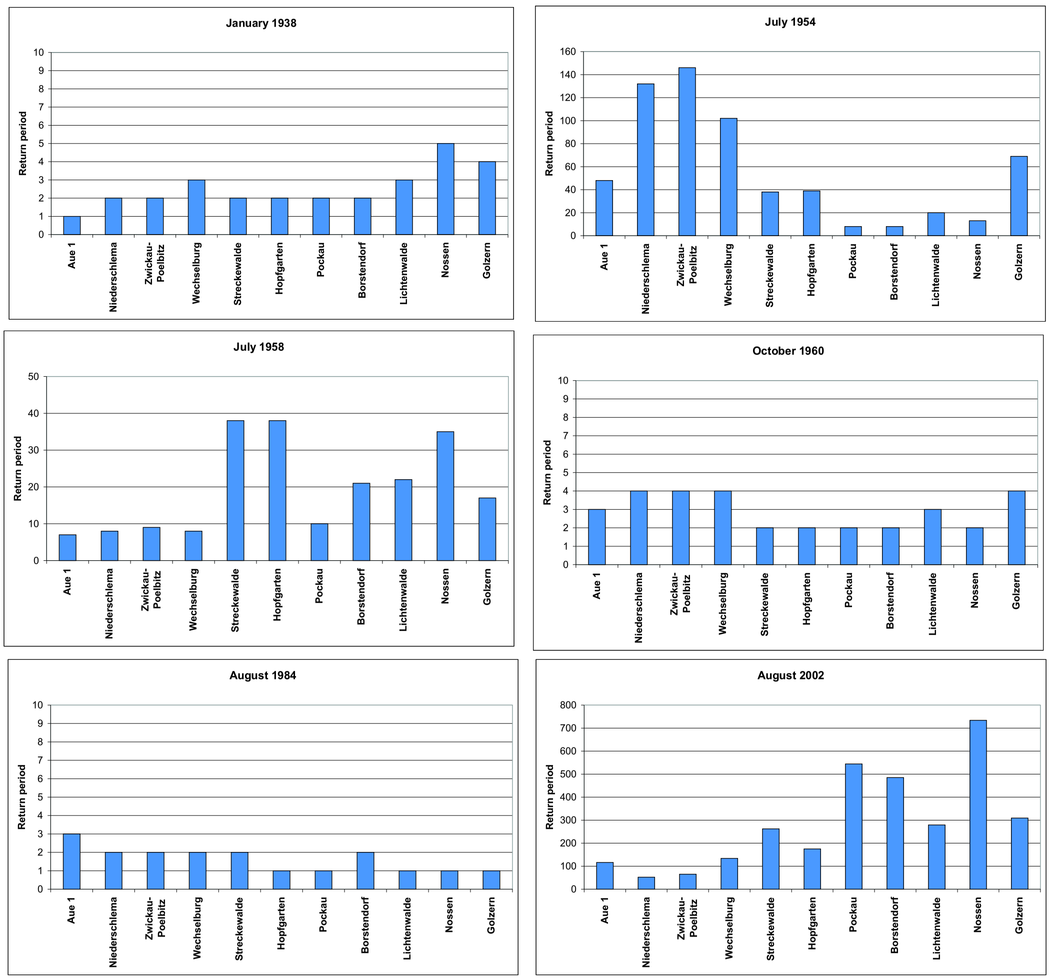

Fig. 9. Variation of return periods for six different floods.

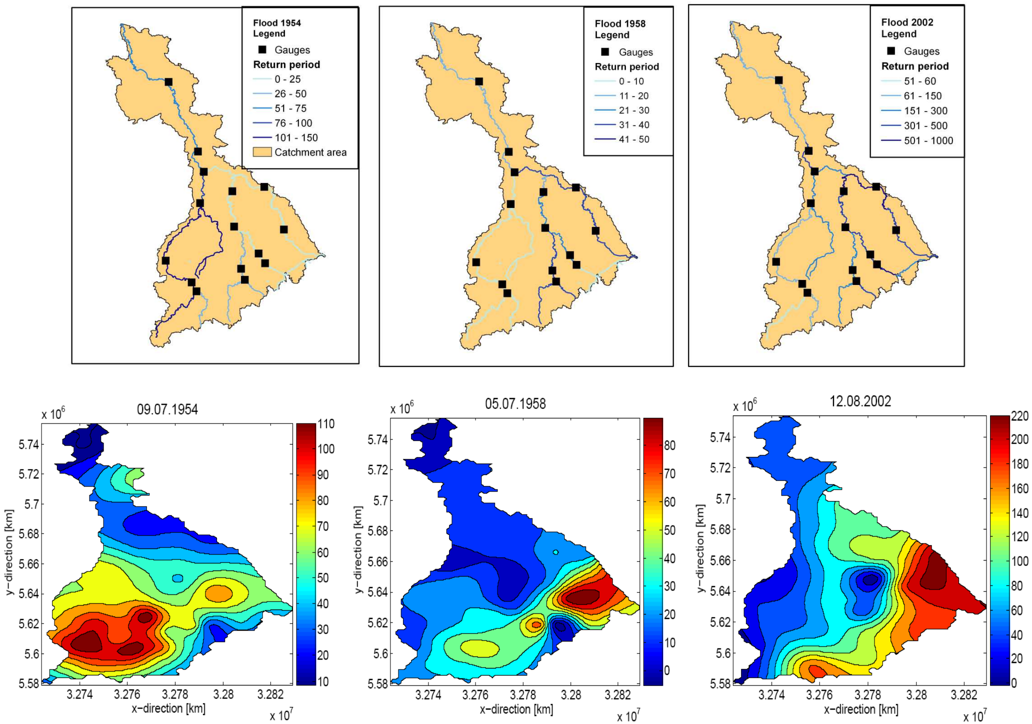

Fig. 10. Estimated return periods (GEV, L-Moments) for the floods in 1954, 1958, 2002 (period 1929–2002 (above)) and the corresponding precipitation fields (below). Note that for a better illustration of the spatial distribution the classes of discharge return periods and precipitation amounts differ.

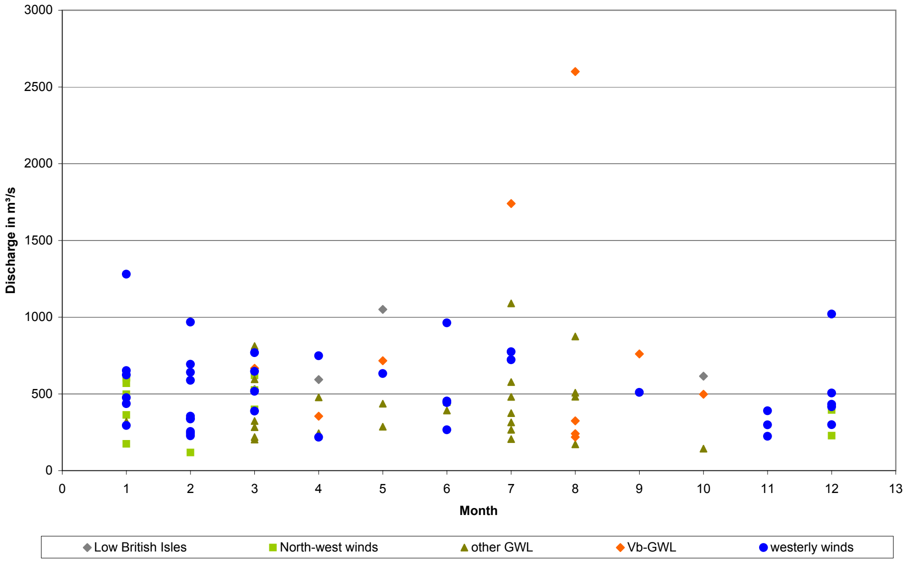

Fig. 11. Monthly distribution of AMS discharges at Golzern and the assigned Großwetterlage.

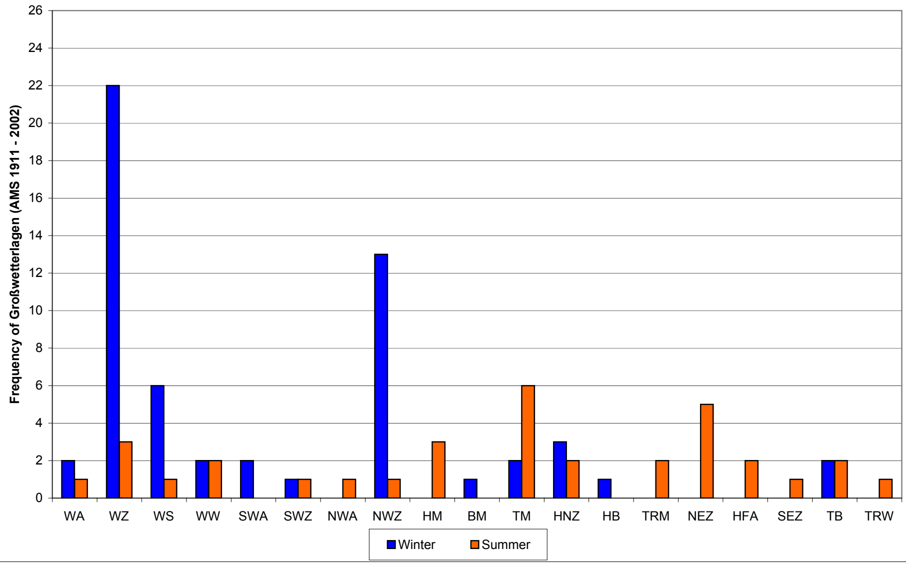

Fig. 12. Histogram of the Großwetterlagen at the gauge Golzern that generated AMS discharges between 1911 and 2002 (abbr. see Table 2).

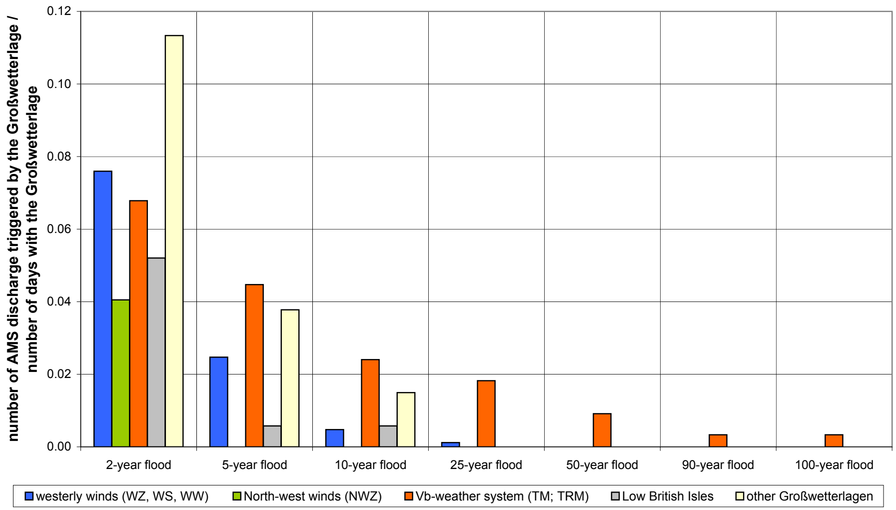

Fig. 13. Flood potential of different Großwetterlagen to cause a flood of a certain return period.